Higgs boson search at ATLAS

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1 Introduction

The 2011 run of the Large Hadron Collider (LHC) at CERN was very successful, with experiments accumulating nearly 5 fb^{-1} of data. Of particular interest was the search for a Standard Model (SM) Higgs boson, the remaining component of the SM that has not yet been definitively observed. This note summarizes the status of this search at the ATLAS experiment [1] using the full 2011 data set of (4.6–4.9) fb^{-1}.

2 Higgs boson search channels

The Higgs boson search is carried out for many different final states. At the LHC, the dominant production mode for a Higgs boson is gluon-gluon fusion ($gg \to H$). For a Higgs boson with mass m_H above about 135 GeV, the dominant decay is into a pair of W or Z gauge bosons; such decays that include leptons in the final state are distinctive enough to search for directly. For lower Higgs boson masses, the dominant decay is into two b-quarks. The very large heavy-flavour multijet background makes it infeasible to search for this decay directly. One can look for rarer but more distinctive decays of the Higgs boson, such as $H \to \gamma\gamma$ or $H \to \tau\tau$, for diboson decays in which one of the gauge bosons is off-shell, or for a Higgs boson produced in association with a W or Z boson. The best sensitivity for $m_H \approx 125$ GeV is obtained from $H \to \gamma\gamma$, followed by $H \to ZZ^{(*)} \to \ell\ell\ell'\ell'$.

2.1 $H\to\gamma\gamma$ channel

The diphoton decay of the Higgs boson is relatively rare (with a branching ratio $\sim 0.2\%$). In order to have good sensitivity in this channel [2], one must have very good $m_{\gamma\gamma}$ resolution as well as good control over non-photon backgrounds. ATLAS achieves a mass resolution of about 1.7% at $m_H = 120$ GeV, and the fraction of non-photon background is less than 30%.

To optimize the expected sensitivity, the analysis is split into nine subchannels with differing mass resolution and expected signal fraction, depending on the kinematics of the photons and whether they converted. The background is modeled with

an exponential fit to the data. Results are shown in Figure 1. The m_H regions (113–115) GeV and (134.5–136) GeV are excluded at 95% CL. A small excess is seen around $m_H = 126.5$ GeV, with a local significance of 2.8σ, or a global significance of 1.5σ when the look-elsewhere effect is taken into account over the m_H range (110–150) GeV.

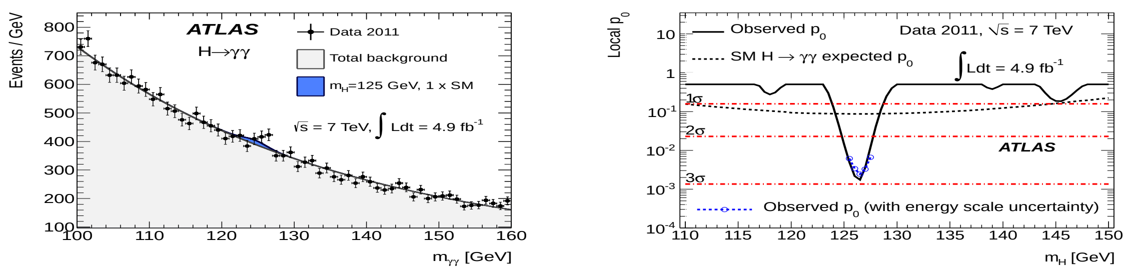

Figure 1: Results from the $H\to\gamma\gamma$ channel [2]. Left: Invariant mass distribution for the entire sample, overlaid with the fitted total background. The expectation for a $m_H = 125$ GeV SM Higgs boson is also shown. Right: Local probability p_0 for the background to fluctuate to the observed number of events or higher. The dashed line shows the expected median local p_0 for the signal hypothesis when tested at m_H.

2.2 $H\to ZZ^{(*)}\to\ell\ell\ell'\ell'$ channel

In this channel [3], one looks for two pairs of opposite-sign, same-flavour leptons (e or μ), with one pair having an invariant mass close to the Z boson mass. This channel has a quite small background and a fully-reconstructed Higgs boson decay, which allows it to have good sensitivity over a wide range of Higgs boson masses, from 600 GeV down to 110 GeV. The background is primarily ZZ diboson production, with smaller contributions from $Z+$jets and $t\bar{t}$.

The results are shown in Figure 2, Row 1. The m_H regions (134–156) GeV, (182–233) GeV, (256–265) GeV, and (268–415) GeV are excluded at 95% CL. Small excesses are seen around 125 GeV, 244 GeV, and 500 GeV with local significances of 2.1σ, 2.2σ, and 2.1σ, respectively. The excess at 125 GeV corresponds to three events that cluster within the m_H mass resolution of 2%: two $2e2\mu$ events at 123.6 and 124.3 GeV, and one 4μ event at 124.3 GeV.

2.3 $H\to WW^{(*)}\to\ell\nu\ell\nu$ channel

This channel [4] is also sensitive over a wide mass range. The event selection requires two isolated, opposite-sign leptons and a large missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$). The

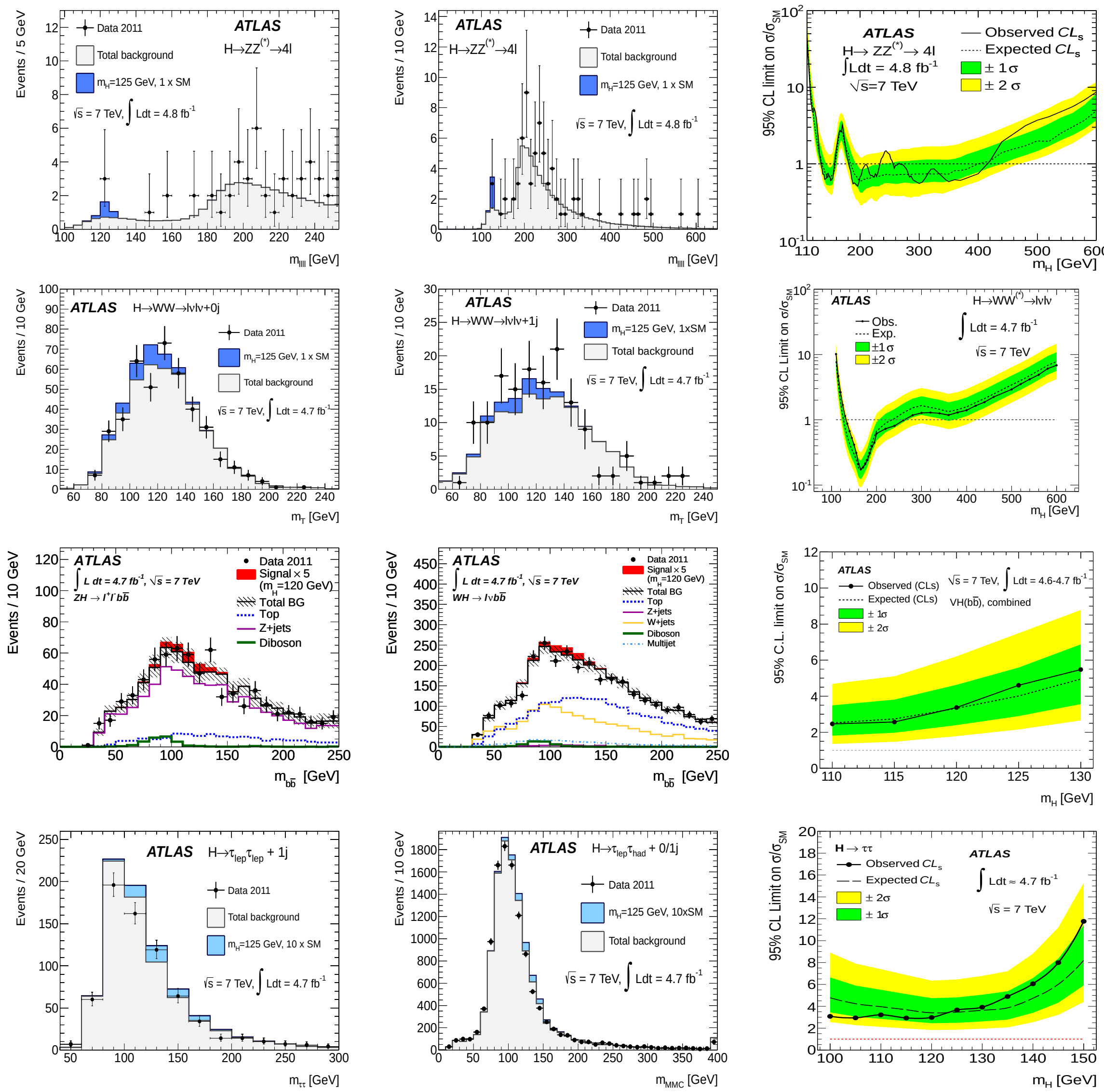

Figure 2: Selected results. Left two columns: data compared with expected background for (Row 1) $m_{4\ell}$ from the $H \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell'\ell'$ channel for 100 GeV $< m_H <$ 250 GeV and for the complete range [3]; (Row 2) m_T from the $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$ channel with 0/1 jets [4]; (Row 3) m_{bb} from the ZH and WH channels [5]; (Row 4) $m_{\tau\tau}$ from the $H \rightarrow \tau_{\rm lep}\tau_{\rm lep} + 1j$ and $H \rightarrow \tau_{\rm lep}\tau_{\rm had} + 0/1j$ channels [6]. An example of the expected signal is also shown (scaled up for some channels to make it more visible). Right: Corresponding exclusion plots, showing the expected (dashed) and observed (solid) 95% CL upper limits on SM Higgs boson production. The dark (green) and light (yellow) bands indicate the expected limits with $\pm 1\sigma$ and $\pm 2\sigma$ fluctuations, respectively.

analysis is divided into subsamples with 0, 1, and ≥ 2 jets, as the background composition is quite different for these cases: for the 0-jet case, the background is dominated by the WW and $Z+$jets processes, while for the 2-jet case, $t\bar{t}$ dominates. As there are two neutrinos in the final state, the Higgs boson mass cannot be reconstructed; the transverse mass m_T is used instead. Results are shown in Figure 2, Row 2. No excess is seen, and the m_H region (133–261) GeV is excluded at 95% CL.

2.4 Other low-m_H channels

Two additional channels are sensitive to a low-mass Higgs boson. In the $V(H\to b\bar{b})$ channel [5], one searches for a Higgs boson produced in association with a vector gauge boson, with the Higgs boson decaying into a $b\bar{b}$ pair. The event selection for this channel requires a gauge boson decay to leptons/neutrinos (one of $W\to\ell\nu$, $Z\to\ell\ell$, or $Z\to\nu\nu$) and exactly two b-tagged jets. The analysis is subdivided in bins of $p_{\mathrm{T}}(V)$. The $H\to\tau\tau$ analysis [6] is divided into $2\ell 4\nu$, $\ell\tau_{\mathrm{had}}3\nu$, and $2\tau_{\mathrm{had}}2\nu$ subchannels; these are then further subdivided according to the number of extra jets in the event. Since there are multiple neutrinos in the final state, the invariant mass $m_{\tau\tau}$ is estimated either using the collinear approximation (assuming the neutrino to be collinear with the visible decay products) or the "missing mass calculator" technique (incorporating the probability distribution for the opening angle in τ decays).

Selected results are shown in Figure 2, Rows 3 and 4. Exclusion limits for these channels range from about 2.5 to 12 times the SM Higgs boson production cross section over the m_H range (100–150) GeV.

2.5 Other high-m_H (diboson) channels

The remaining diboson channels are sensitive to higher Higgs boson masses. For the $H\to ZZ\to\ell\ell\nu\nu$ channel [7], events with a $Z\to\ell\ell$ decay and large $E_{\mathrm{T}}^{\mathrm{miss}}$ are selected. Different selection requirements are made for m_H above or below 280 GeV. For $H\to ZZ\to\ell\ell qq$ [8], events are selected with one $Z\to\ell\ell$ decay, one $Z\to jj$ decay, and small $E_{\mathrm{T}}^{\mathrm{miss}}$. As the fraction of heavy-flavour in the final state is quite different for signal and background, this channel is divided into "tagged" (with two identified b-jets) and "untagged" subchannels. The principal backgrounds for these two channels are $Z+$jets, $t\bar{t}$, and ZZ. For the $H\to WW\to\ell\nu qq$ channel [9], events are selected with an isolated lepton, large $E_{\mathrm{T}}^{\mathrm{miss}}$, and a $W\to jj$ decay. This analysis is divided into subchannels according to the number of additional jets in the event.

Results are shown in Figure 3. The $ZZ\to\ell\ell\nu\nu$ channel excludes at 95% CL the m_H range (320–560) GeV, while the $ZZ\to\ell\ell qq$ channel excludes the ranges (300–322) GeV and (353–410) GeV. Exclusions from the $WW\to\ell\nu qq$ channel are 2–10 times the SM cross section.

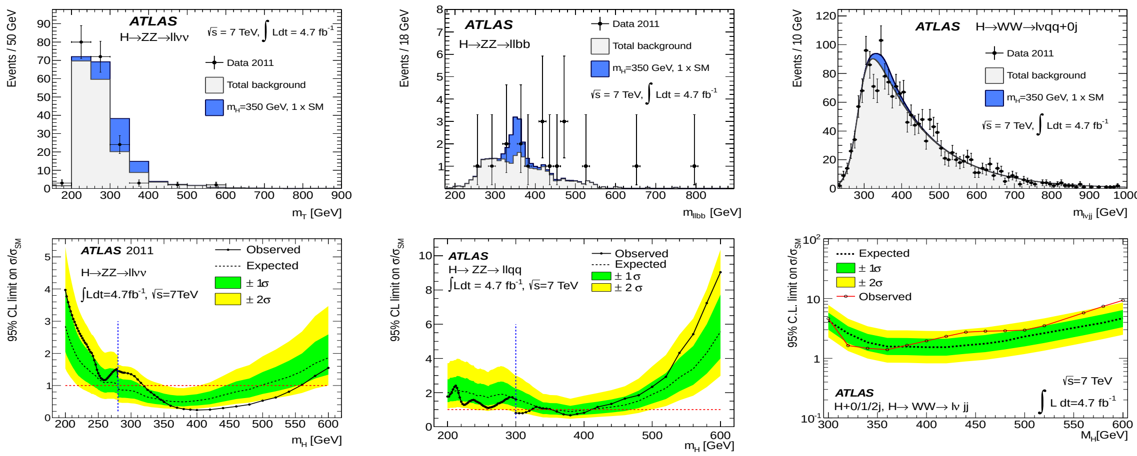

Figure 3: Selected results from the remaining diboson channels. Top: data and expected background for $H \to ZZ \to \ell\ell\nu\nu$, showing m_T [7] (left); $H \to ZZ \to \ell\ell qq$, showing $m_{\ell\ell bb}$ for the high-m_H, tagged subchannel [8] (middle); and $H \to WW \to \ell\nu qq$, showing $m_{\ell\nu jj}$ for the 0-jet subchannel [9] (right). The expectations for a Higgs boson of $m_H = 350$ GeV are also shown. Bottom: Corresponding exclusion plots (see Figure 2).

3 Combination of all channels

For the final results, all these channels are combined [10]. Systematic uncertainties are taken to be either 100% correlated or uncorrelated between channels. The results are shown in Figure 4. The m_H ranges (111.4–116.6) GeV, (119.4–122.1) GeV, and (129.2–541) GeV are excluded at 95% CL, and the m_H range (130.7–506) GeV is excluded at 99%. An excess is seen around $m_H = 126$ GeV, with a local significance of 3.0σ. The global significance is approximately 15% over the full range (100–600) GeV and (5–7)% over the range (110–146) GeV, corresponding to the range at low-m_H not excluded by the previous LHC SM Higgs boson combined search at 99% CL [11]. If the excess is interpreted as a SM Higgs boson, the corresponding cross section ratio at $m_H = 126$ GeV is $\mu = \sigma_{\text{obs}}/\sigma_{\text{SM}} = 1.1 \pm 0.4$, consistent with the SM value of 1.0. The excess is observed only in the $H \to \gamma\gamma$ and $H \to \ell\ell\ell'\ell'$ channels; however, none of the other channels are inconsistent with a SM Higgs boson at this mass.

4 Summary

From the 2011 data, ATLAS excludes at 95% CL the m_H range (111.4–541) GeV, except for the regions (116.6–119.4) GeV and (122.1–129.2) GeV. An excess is seen in the $H \to \gamma\gamma$ and $H \to \ell\ell\ell'\ell'$ channels at $m_H \approx 126$ GeV which is consistent with a

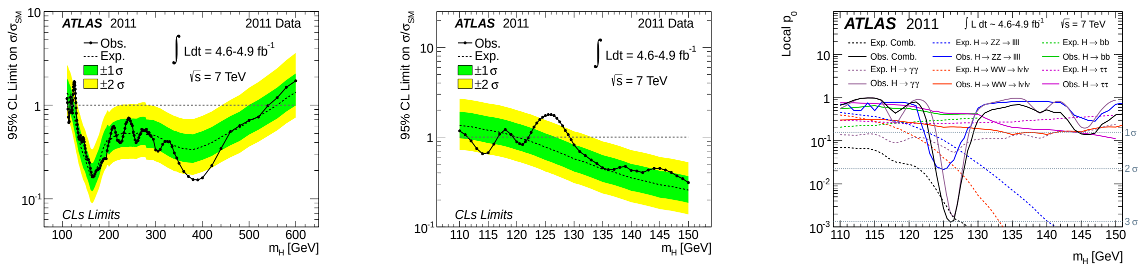

Figure 4: Left, middle: Combined exclusion limits for the full mass range and for $m_H < 150$ GeV [10] (see Figure 2). Right: Local probability p_0 for the background to fluctuate to the observed number of events or higher, by channel, for $m_H < 150$ GeV. Dashed lines show the expected median local p_0 for the signal hypotheses at m_H.

SM Higgs boson. The chance of this being due to a background fluctuation is 15% over the full mass range, or (5–7)% over (110–146) GeV.

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